

KiloHertz quasi-periodic oscillations difference frequency exceeds inferred spin frequency in 4U 1636–53

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ABSTRACT

Recent observations of the low-mass X-ray binary 4U 1636–53 with the *Rossi X-ray Timing Explorer* show, for the first time, a kiloHertz quasi-periodic oscillation (kHz QPO) peak separation that exceeds the neutron star spin frequency as inferred from burst oscillations. This strongly challenges the sonic-point beat frequency model for the kHz QPOs found in low-mass X-ray binaries. We detect two simultaneous kHz QPOs with a frequency separation of 323.3 ± 4.3 Hz in an average Fourier power spectrum of observations obtained in September 2001 and Januari 2002. The lower kHz QPO frequency varied between 644 Hz and 769 Hz. In previous observations of this source the peak separation frequency was ~ 250 Hz at a lower kHz QPO frequency of ~ 900 Hz. Burst oscillations occur in 4U 1636–53 at ~ 581 Hz and possibly at half that frequency (290.5 Hz). This is the first source where the peak separation frequency is observed to change from less than (half) the burst oscillation frequency to more than that. This observation contradicts all previously formulated implementations of the sonic-point beat frequency model except those where the disk in 4U 1636–53 switches from prograde to retrograde. We discuss possible ways out for the sonic-point beat frequency model and other models for the kHz QPOs.

Key words: accretion, accretion disks — stars: individual (4U 1636–53) — stars: neutron — X-rays: stars

1 INTRODUCTION

In recent years kiloHertz quasi-periodic oscillations (kHz QPOs) have been found in power spectra of more than 20 low-mass X-ray binaries (LMXBs) using observations made with the *Rossi X-ray Timing Explorer* (*RXTE*) satellite (van der Klis 2000). In most sources the kHz QPOs are found in pairs. The high frequencies of these QPOs suggest that at least one of the two peaks reflects the orbital motion of matter close to the neutron star. Another high frequency phenomenon was detected with *RXTE*: during some type I X-ray bursts nearly coherent oscillations which slightly drift in frequency, the so-called burst oscillations, have been observed in the power spectra of ten sources (for a review see Strohmayer 2001). The X-ray flux-modulation is consistent with being due to the changing aspect of a drifting hot spot on the surface of the neutron star. Therefore, these burst oscillations are thought to reflect the spin frequency of the

neutron star. In high luminosity ‘Z’-source LMXBs QPOs at low frequencies were found with the *EXOSAT* and *GINGA* satellites (for a review see van der Klis 1989). Observations with the *RXTE* satellite have also revealed low-frequency QPOs in a number of atoll sources (e.g. Homan et al. 1998; Ford & van der Klis 1998).

The atoll source 4U 1636–53 is one of the few sources that displays all of the high-frequency QPO phenomena that have been observed in LMXBs; two kHz QPOs have been observed (Zhang et al. 1996; Wijnands et al. 1997) as well as a sideband to the lower of the two kHz QPOs (Jonker, Méndez & van der Klis 2000) and burst oscillations at ~ 581 Hz (Zhang et al. 1997; Strohmayer et al. 1998). Miller (1999) presented evidence that these oscillations are in fact the second harmonic of the neutron star spin of ~ 290.5 Hz. However, using another dataset these findings were not confirmed (Strohmayer 2001).

Since the frequency difference between the two kHz QPO peaks (the peak separation, $\Delta\nu$) is nearly equal to (half) the burst oscillation frequency a beat frequency mech-

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anism was proposed for the kHz QPOs (Strohmayer et al. 1996). In such a model the higher frequency QPO is attributed to the orbital frequency of clumps of plasma at a special radius near the neutron star while the lower frequency QPO is due to the beat between the orbital frequency and the stellar spin frequency. A specific model incorporating the beat frequency mechanism, the sonic-point beat frequency model, is now one of the leading models explaining kHz QPOs in LMXBs (Miller, Lamb & Psaltis 1998). However, subsequent findings complicated the picture. As was first shown in Sco X-1, the peak separation decreases as the kHz QPO frequencies increase (van der Klis et al. 1997). Furthermore, in 4U 1636-53 the peak separation was found to be less than half the burst oscillation frequency (Méndez, van der Klis & van Paradijs 1998). These findings could be explained within the sonic point beat frequency model (Lamb & Miller 2001) by taking into account the effect of the inward velocity of the plasma on the emerging kHz QPO frequencies. A firm prediction of this revised sonic-point beat frequency model is that for prograde spinning accretion disks the kHz QPO peak separation is smaller than the neutron star spin frequency. This follows from the detailed description of the plasma flow patterns in this model which produce a number of corrections to the observed frequencies relative to the true orbital and beat frequency, all of which are expected to make $\Delta\nu$ smaller (Lamb & Miller 2001). Indeed, until now, in various sources the peak separation was always found to be consistent with, or less than (half) the burst oscillation frequency.

In this *Letter* we show that in recent observations of 4U 1636-53 the kHz QPO peak separation is significantly larger than half the burst oscillation frequency. Using other observations Méndez, van der Klis & van Paradijs (1998) had shown earlier that the peak separation was significantly smaller than half the burst oscillation frequency. This means that in order for the sonic-point beat frequency to explain both observations further changes will have to be made in the description of the flow pattern. The only change in the flow pattern previously described that could produce the observed change in the separation frequency is that in which the accretion disk changes from prograde to retrograde when the lower kHz QPO moves from ~ 750 Hz to ~ 800 Hz.

2 OBSERVATIONS AND ANALYSIS

4U 1636-53 was observed in September 2001 and January 2002 with the proportional counter array (PCA; Jahoda et al. 1996) onboard the *RXTE* satellite (Bradt, Rothschild & Swank 1993). Due to the reduced duty cycle of the PCA detectors only a subset of the 5 detectors is operational for most of the time. In this analysis we only used data in which 4 of the 5 detectors were operational. A log of the observations is provided in Table 1. In total ~ 28.4 ksec of data were used. Data were obtained using a so called Event-mode in which information on detected X-ray photons is stored onboard and subsequently telemetered to the ground on an event-to-event basis. The time resolution of the data is $\sim 125\mu\text{s}$ and *RXTE*'s effective energy range (2–60 keV) is covered by 64 channels.

Using this data we calculated power density spectra of segments of 64 s up to a Nyquist frequency of 4096 Hz in

one energy band covering the total PCA energy range. We used a dynamical power spectrum displaying consecutive power spectra rebinned to a frequency resolution of 2 Hz and a time resolution of 128 s to visualize the time evolution of the lower kHz QPO for all observations except for the power spectra of observation 60032-01-21-00 which were rebinned to a time resolution of 162s (segment 7) and 256s (segment 8), and the power spectra of observation 60032-01-22-00, which were treated separately. We traced the frequency of the lower kHz QPO and fitted the power spectrum in a window of 200 Hz centered on the traced frequency with a Lorentzian and a constant. All peaks in each power spectrum of 128 s, 162 s, and 256 s had a significance of $\sim 3\sigma$ or more. The frequency of the bin associated with the peak of the fitted Lorentzian was taken to be the frequency of the QPO in that power density spectrum. Finally, we used the shift-and-add method described by Méndez, van der Klis & van Paradijs (1998) to shift the lower kHz QPO to the same (arbitrary) frequency in each power spectrum before averaging. This assures that at least for timescales longer than 256 s the determined peak separation is not influenced by the fact that the two kHz QPOs have a different frequency-amplitude relation (Méndez, van der Klis & Ford 2001).

We averaged the aligned power spectra and fitted the average power spectrum from 256–1500 Hz with a constant, to represent the power introduced by the Poisson counting noise, and two Lorentzians to represent the two kHz QPOs. Errors on the fit parameters were determined using $\Delta\chi^2 = 1.0$ (1σ single parameter). The observation 60032-01-22-00 was treated separately since we were not able to find a more than 3σ lower kHz QPO using data stretches shorter than or equal to 256 s. Instead we averaged the power spectra in this observation without shifting the data. We note that by doing so we may have artificially introduced deviations in the kHz QPO peak separation if the two kHz QPOs moved in frequency during the observation for reasons outlined above.

The fits of the average power spectra were good, with a reduced χ^2 slightly larger than 1 for 146 degrees of freedom. We found that, combining all observations, except 60032-01-22-00, the frequency separation between the two kHz QPO peaks was 323.3 ± 4.3 Hz, significantly larger than 290.5 Hz the putative spin frequency according to an analysis of Miller (1999), but still significantly smaller than 581 Hz, the frequency of the strong burst oscillations found by Zhang et al. (1997) and Strohmayer et al. (1998) (see Figure 1). We then divided the data set into three parts according to the frequency of the lower kHz QPO and measured the peak separation in each of the parts. For each part we also averaged the power spectra *without* shifting in order to measure the average frequency of the lower kHz QPO and that of a low-frequency QPO changing in frequency from ~ 24 –42 Hz. In Table 2 we present our results on the kHz QPOs. The fractional rms amplitude of the low-frequency QPO changed from 7.8 ± 0.6 per cent to 4.3 ± 0.7 per cent (2–60 keV) while its frequency increased from 23.6 ± 2.4 Hz to 42 ± 4 Hz and its FWHM was consistent with being constant at 26 ± 9 Hz. In Figure 2 we plot the measured peak separation ($\Delta\nu$) as a function of the frequency of the lower and upper kHz QPO (*left* and *right* panel, respectively). The squares are our new measurements using the shift-and-add method, the diamond is our measurement using observation 60032-01-22-00, and the dots are the measurements of Di Salvo, Méndez

Table 1. Log of the observations used in this analysis.

Observation ID	Used segments	Amount of good data (ksec)	Count rate ^a cnt/s/PCU
60032-01-09-00	1	3.3	230
60032-01-09-03	all	2.5	220
60032-01-19-00	1, 2, 3	8.6	205
60032-01-21-00	7, 8	6.7	180
60032-01-22-00	1, 2	7.3	180

^a Average background subtracted count rate per PCU (2–60 keV)

& van der Klis (2002) based on *RXTE* data obtained from 1996–2000 (see also Wijnands et al. 1997; Méndez, van der Klis & van Paradijs 1998). Clearly, $\Delta\nu$ changes from more than half the burst oscillation frequency to less than that. The average $\Delta\nu$ of the three leftmost points is 327.2 ± 4.2 Hz and that of the dots is 247.1 ± 1.9 Hz making the jump in $\Delta\nu$ 70.1 ± 4.6 Hz.

3 DISCUSSION

We found that in 4U 1636–53 the kHz QPO frequency separation ($\Delta\nu$) changes as a function of the frequency of the lower kHz QPO from 323.3 ± 4.3 Hz to 242.4 ± 3.6 Hz (Fig. 2 *left*); the maximum peak separation is significantly larger than 290.5 Hz (half the burst oscillation frequency of ~ 581 Hz see Section 1), while the minimum peak separation is significantly smaller than that. The change in $\Delta\nu$ as a function of *upper* kHz QPO frequency is abrupt; the data are consistent with a sudden jump at $\nu = 1050$ Hz (Fig. 2 *right*) symmetric around 290.5 Hz. We note that similar jumps in $\Delta\nu$ as a function of the upper kHz QPO have also been seen in 4U 1728–34 and 4U 1608–52, although in those cases $\Delta\nu$ always remained smaller or equal to (half) the burst oscillation frequency [Méndez & van der Klis 1999; Chakrabarty, D. (Talk 2001) showed that burst oscillations occur at ~ 619 Hz in 4U 1608–52 while the maximum $\Delta\nu \sim 310$ Hz; Méndez et al. 1998, see also the comment about 4U 1608–52 in Lamb & Miller 2001]. This is the first time that the kHz peak separation has been shown to be significantly larger than the inferred neutron star spin frequency contrary to certain beat frequency model predictions, see below, and also the first time that $\Delta\nu$ has been seen to vary between less and more than (half) the burst oscillation frequency.

In previous work burst oscillations detected in the dipping burster 4U 1916–15 at ~ 272 Hz also seemed to occur at too low a frequency for $\Delta\nu$ (Galloway et al. 2001). However, in that source the kHz QPOs are weak and sometimes very broad, therefore whole segments of several ksec were needed to obtain a detection (Boirin et al. 2000). This means that there is no certainty that the kHz QPOs were detected simultaneously or that their apparent separation was not affected by frequency shifts combined with changes in their power ratio. Therefore, the measured $\Delta\nu$ may not reflect the true peak separation. In the current work, using the shift-and-add method we excluded the possibility that effects changing $\Delta\nu$ on timescales longer than 256 s have influenced the observed $\Delta\nu$. However, on timescales shorter than 256 s the lower and upper kHz frequencies do change, as was recently

found by Yu, van der Klis & Jonker (2001) and Yu & van der Klis (2002). Especially changes associated with the 5–6 Hz QPO in Sco X–1 are relatively large (~ 20 Hz). However, those ~ 5 –6 Hz QPOs are only found when atoll and Z sources are in a high-luminosity state (e.g. Middleditch & Priedhorsky 1986; Wijnands, van der Klis & Rijkhorst 1999). Changes in the kHz QPO frequencies associated with milliHz QPOs present in 4U 1636–53 and 4U 1608–52 in a small luminosity interval (Revnivtsev et al. 2001) are small (less than a Hz; Yu & van der Klis 2002). Such small changes are not likely to alter our findings significantly, although we note that such a milliHz QPO was present during some of the observations.

All versions of the sonic-point beat frequency model described so far involving a prograde spinning accretion disk (Miller, Lamb & Psaltis 1998; Lamb & Miller 2001) predict that $\Delta\nu$ is always less than or equal to the spin frequency of the neutron star for Keplerian orbital frequencies larger than the neutron star spin frequencies; this prediction is now falsified. The principal motivation for a beat frequency model is the relative closeness of the frequency of the inferred spin to $\Delta\nu$. That the frequencies are not exactly equal is explained in the sonic-point beat frequency model by the way in which the beat frequency interaction produces the observed frequencies. The key element is the radial motion of the plasma clumps near the sonic radius (Lamb & Miller 2001). This makes the observed lower kHz QPO frequency somewhat larger than the beat frequency since it squeezes the spatial separation between peaks of enhanced mass flow. It also makes the upper kHz QPO frequency smaller than the orbital frequency since it makes the clump’s footpoint move backward in a corotating frame.

Strohmayer (2001) showed that it is still unclear whether the burst oscillations in 4U 1636–53 reflect the spin frequency of the neutron star or its second harmonic. Therefore, one might argue that the spin frequency is really at 581 Hz (not 290.5 Hz) and hence that $\Delta\nu$ is less than the spin frequency. This would, however, take away the principal motivation of beat frequency models, since the neutron star spin frequency and that of the kHz QPO peak separation are in that case completely different.

Perhaps it is possible to find other effects in the plasma flow patterns than those discussed by Lamb & Miller (2001) (which all make $\Delta\nu$ smaller) which lead to larger values of $\Delta\nu$ at lower kHz QPO frequencies. Fully relativistic simulations of the gas flow and radiation transport reported by Lamb & Miller (2001) have not, so far, shown evidence for this. If, however, the sense of rotation of (part of) the accretion disk would change from prograde to retrograde when

Table 2. The kHz QPO frequency separation ($\Delta\nu$), the frequency, the fractional rms amplitude (2–60 keV), and the full-width-at-half-maximum (FWHM) of the lower kHz QPO ($\nu_{lower\ kHz}$), the fractional rms amplitude (2–60 keV) and the FWHM of the upper kHz QPO ($\nu_{upper\ kHz}$).

Lower kHz QPO			Upper kHz QPO		Peak separation
rms (%)	FWHM (Hz)	$\nu_{lower\ kHz}$ (Hz) ^a	rms (%)	FWHM (Hz)	$\Delta\nu$ (Hz)
7.7±0.4	52±8	644.2±3.2	6.9±0.5	52±11	326.9±5.3
7.6±0.3	15.7±2.3	687.8±2.1	6.8±0.9	74±35	325.1±11.5
8.5±0.1	8.1±0.3	723.0±0.9	5.6±0.7	83±31	329.5±8.9
8.7±0.1	7.2±0.7	769.2±1.2	5.1±0.9	139±62	288.6±31

^a The frequency of the lower kHz QPO ($\nu_{lower\ kHz}$) and all the parameters on the first row were determined without shifting the data.

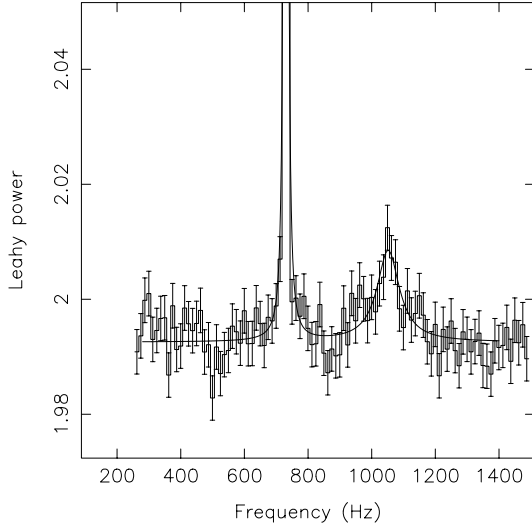


Figure 1. Average power density spectrum combining all shifted data used in this paper. The peak of the lower kHz QPO is off the vertical scale. The kHz QPO frequency separation is 323.3 ± 4.3 Hz. The power spectra have been shifted before averaging, therefore, only the frequency difference between the peaks is meaningful.

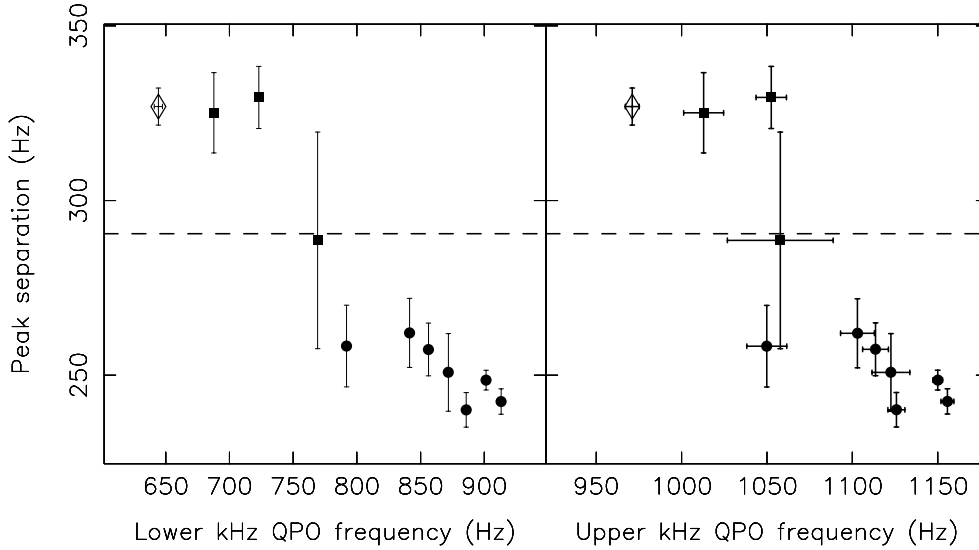


Figure 2. *Left:* The kHz QPO frequency separation as a function of the frequency of the lower kHz QPO. *Right:* The kHz QPO frequency separation as a function of the frequency of the upper kHz QPO. The frequency of half the burst oscillation frequency (290.5 Hz) is indicated by the dashed line. The peak separation varies from significantly more than half the burst oscillation frequency [diamond (unshifted data) and squares (shifted data); this work] to significantly less than that (dots; Di Salvo et al. 2002; see also Wijnands et al. 1997 and Méndez et al. 1998). Error bars on the frequency of the lower kHz QPO are generally smaller than the size of the symbols.

$\Delta\nu$ changes from less to more than the spin frequency, then the observations could still be in accordance with current formulations of the sonic-point beat frequency model. This also requires that in our observations the lower kHz QPO reflects the (near) Keplerian orbital frequency, whereas for those points in Figure 2 where $\Delta\nu$ is smaller than half the burst oscillation frequency, the Keplerian orbital motion is represented by the upper kHz QPO. Although, contrary to other atoll sources such as 4U 1728–34 and 4U 1608–52, in 4U 1636–53 the fractional rms amplitude of the lower kHz QPO is higher than that of the upper kHz QPO, this seems unlikely since the change in fractional rms amplitude of the lower and upper kHz QPO and $\Delta\nu$ as a function of the lower kHz QPO frequency in 4U 1636–53 (this work; Jonker, Méndez & van der Klis 2000; Wijnands et al. 1997; Di Salvo, Méndez & van der Klis 2002) fits in with the observed trends in the atoll sources 4U 1728–34 and 4U 1608–52 (Méndez, van der Klis & Ford 2001), where $\Delta\nu$ is less than or consistent with (half) the burst oscillation frequency (Strohmayer et al. 1996; Méndez & van der Klis 1999).

We detected a low-frequency QPO between ~ 25 –40 Hz simultaneously with the kHz QPO pair. The relation between this low-frequency QPO and the lower kHz QPO (see Psaltis, Belloni & van der Klis 1999) is similar to the one found by Ford & van der Klis (1998) for 4U 1728–34. It has been suggested that such low-frequency QPOs in atoll sources are related to the Z source Horizontal Branch Oscillations (e.g. Homan et al. 1998). According to the magnetospheric beat frequency model these Horizontal Branch Oscillations originate near the magnetospheric radius (Alpar & Shaham 1985; Lamb et al. 1985). The frequency of the low-frequency QPO in 4U 1636–53 increased as the frequency of the lower kHz QPO increased. Therefore, if the disk near the sonic radius is indeed retrograde in our observations the retrograde annulus of the accretion disk must extend at least up to the magnetospheric radius if the sonic-point and magnetospheric beat frequency models both apply. Partially retrograde spinning accretion disks have been proposed as a possible explanation for observed torque reversals (Bildsten et al. 1997) in slowly rotating neutron stars with a dipole magnetic field strength of 10^{11-12} Gauss (van Kerkwijk et al. 1998). Modelling by van Kerkwijk et al. (1998) shows that the accretion disk can get inclinations of more than 90 degrees. It is not clear if their work is applicable to the case of low-magnetic field LMXBs. Clearly, allowing disks with alternating rotation senses complicates the sonic-point beat frequency interpretation of the kHz QPOs considerably.

Marković & Lamb (2002) showed that the model (Stella & Vietri 1999) describing the kHz QPO frequencies and the low-frequency QPO as three general relativistic frequencies of test-particle motion close to a neutron star or black hole was unable to reproduce the observed QPO frequencies without resorting to extremely elliptical particle orbits. Psaltis & Norman (2001) presented the so-called transition layer model, in which the QPO frequencies, similar to the model of Stella & Vietri (1999), are largely set by the properties of the metric, without the need for elliptical orbits. This transition layer model is until now the only model capable of explaining the observed sidebands to the lower kHz QPO (Psaltis 2001). However, in that model the fact that the ratio between (half) the burst oscillation frequency and

$\Delta\nu$ is close to unity in several kHz QPO sources remains unexplained.

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REFERENCES

- Alpar M. A., Shaham J., 1985, *Nat*, 316, 239
- Bildsten L. et al., 1997, *ApJS*, 113, 367+
- Boirin L., Barret D., Olive J. F., Blosier P. F., Grindlay J. E., 2000, *A&A*, 361, 121
- Bradt H. V., Rothschild R. E., Swank J. H., 1993, *A&AS*, 97, 355
- Di Salvo T., Méndez M., van der Klis, 2002, *ApJ*, , in prep
- Ford E. C., van der Klis M., 1998, *ApJ*, 506, L39
- Galloway D. K., Chakrabarty D., Munro M. P., Savov P., 2001, *ApJ*, 549, L85
- Homan J., van der Klis M., Wijnands R., Vaughan B., Kuulkers E., 1998, *ApJ*, 499, L41
- Jahoda K., Swank J. H., Giles A. B., Stark M. J., Strohmayer T., Zhang W., Morgan E. H., 1996, *Proc. SPIE*, 2808, 59
- Jonker P. G., Méndez M., van der Klis M., 2000, *ApJ*, 540, L29
- Lamb F. K., Miller M. C., 2001, *ApJ*, 554, 1210
- Lamb F. K., Shibasaki N., Alpar M. A., Shaham J., 1985, *Nat*, 317, 681
- Méndez M., van der Klis M., Ford E. C., 2001, *ApJ*, 561, 1016
- Marković D., Lamb F. K., 2002, *MNRAS*, astro-ph, 009169
- Méndez M., van der Klis M., 1999, *ApJ*, 517, L51
- Méndez M., van der Klis M., Wijnands R., Ford E. C., van Paradijs J., Vaughan B. A., 1998, *ApJ*, 505, L23
- Méndez M., van der Klis M., van Paradijs J., 1998, *ApJ*, 506, L117
- Middleditch J., Priedhorsky W. C., 1986, *ApJ*, 306, 230
- Miller M. C., Lamb F. K., Psaltis D., 1998, *ApJ*, 508, 791
- Miller M. C., 1999, *ApJ*, 515, L77
- Psaltis D., Norman C., 2001, *ApJ*, , submitted
- Psaltis D., Belloni T., van der Klis M., 1999, *ApJ*, 520, 262
- Psaltis D., 2001, *Advances in Space Research*, , submitted, Talk presented at the 33rd COSPAR Scientific Assembly, Warsaw, Poland, 16-23 July 2000, astro-ph/0012251
- Revnivtsev M., Churazov E., Gilfanov M., Sunyaev R., 2001, *A&A*, 372, 138
- Stella L., Vietri M., 1999, *Phys. Rev. Lett*
- Strohmayer T. E., Zhang W., Swank J. H., Smale A., Titarchuk L., Day C., Lee U., 1996, *ApJ*, 469, L9
- Strohmayer T. E., Zhang W., Swank J. H., White N. E., Lapidus I., 1998, *ApJ*, 498, L135
- Strohmayer T. E., 2001, *Advances in Space Research*, 28, 511
- van der Klis M., Wijnands R. A. D., Horne K., Chen W., 1997, *ApJ*, 481, L97
- van der Klis M., 1989, *ARA&A*, 27, 517
- van der Klis M., 2000, *ARA&A*, 38, 717
- van Kerkwijk M. H., Chakrabarty D., Pringle J. E., Wijers R. A. M. J., 1998, *ApJ*, 499, L27
- Wijnands R. A. D., van der Klis M., van Paradijs J., Lewin W. H. G., Lamb F. K., Vaughan B., Kuulkers E., 1997, *ApJ*, 479, L141
- Wijnands R., van der Klis M., Rijkhorst E., 1999, *ApJ*, 512, L39
- Yu W., van der Klis M., 2002, *ApJ*, 567, L67

- Yu W., van der Klis M., Jonker P. G., 2001, ApJ, 559, L29
Zhang W., Lapidus I., White N. E., Titarchuk L., 1996, ApJ,
469, L17
Zhang W., Lapidus I., Swank J. H., White N. E., Titarchuk L.,
1997, IAU Circ, 6541, 1+